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Exploitable areas and environmental conditions for the W2Power floating wind energy technology

Milestone 23a

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DemoWind
Delivering cost reduction in offshore wind

CONTENTS

1. SUMMARY

The report categorises deep-water regions of the world according to their wind resource and its quality with a view to identifying the most suitable areas for the commercialisation of deep-water wind – including, but not limited to, the W2Power floating wind technology. An analysis is carried out on the available resource data, drawing on additional parameters and criteria in order to determine the scale and importance of high-quality deepwater wind energy resource in the context of each country (relative to other resources and countries). An objective of this study is to shed light on where, and in what context, floating wind power in deep water could be commercialised.

2. INTRODUCTION

After expanding greatly for more than 25 years – and especially after showing unexpectedly strong cost reductions since 2016, as illustrated in Fig. 1 – offshore wind has today become a major supply source of new renewable electricity along with onshore wind and solar PV.

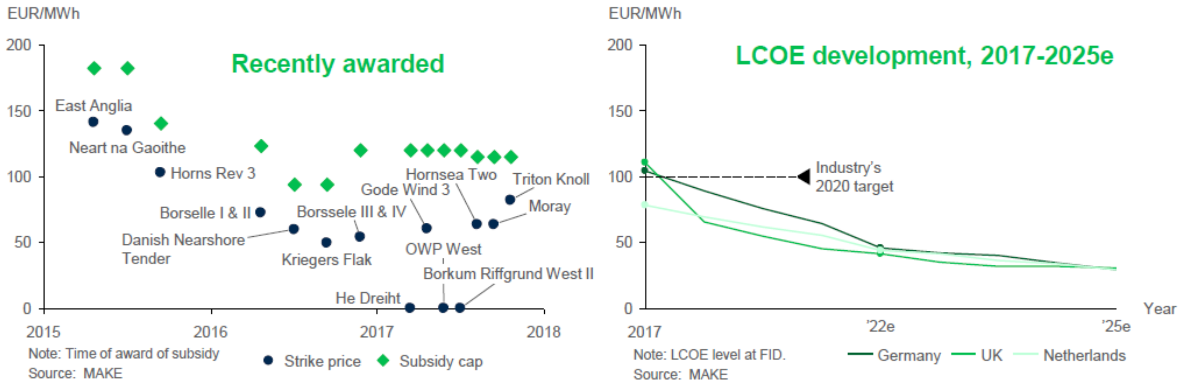

Fig.1 Some offshore projects awarded 2015-18 and falling prices for conventional bottom-fixed. *Source:* MAKE Consulting.

These achievements and the prospect of "subsidy-free" offshore wind parks have caused a large influx of capital and huge expectations to continued growth of the offshore wind sector.

With total wind power capacity currently around 570 GW [1], wind industry organisations and public planners expect accelerating offshore growth in offshore from the 20 GW of capacity installed today. The offshore wind industry is expected to deliver 5 to 6 times that capacity already during the next decade. IRENA remarks that if the world is to meet the goals of the Paris Climate Agreement, the pace of offshore wind power installations will need to grow significantly. Offshore wind technology allows countries around the world to exploit greater wind resources, developing gigawatt-scale programmes close to densely populated coastal areas. This makes offshore wind an important part of the portfolio of technologies available to decarbonise the energy sector of many countries. Thus, IRENA estimates offshore wind growing to more than 520 GW installed by 2050, with 130 GW by 2030. See Fig. 2.

[1] *Global Wind Report 2018,* Global Wind Energyt Council April 2019.

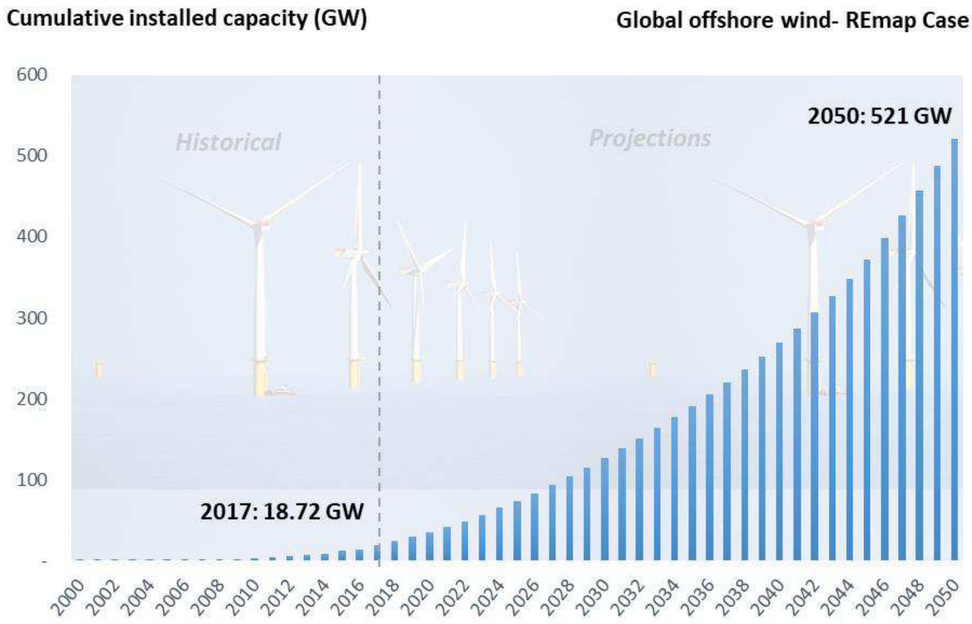

Fig. 2. IRENA scenario for global offshore wind published in September 2018 [2].

Figure 3a and 3b, showing similar estimates from the Carbon Trust, captures the challenges of expanding from the 20 GW of today to the 120 GW expected (in their analysis) by 2030. If achieved, offshore wind globally will by 2030 supply as much renewable power as biomass today: 122 GW by end of 2017 [3]. Biomass is the 4th-largest important source of renewable electricity today, after hydro, onshore wind and solar PV.

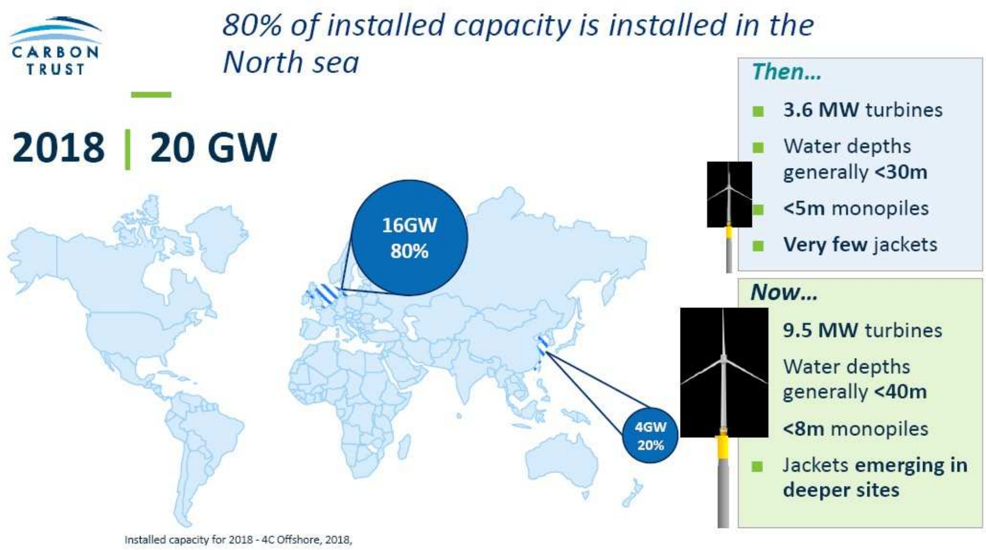

Fig. 3a. Current installed capacities of offshore wind showing some changes in turbine and installation conditions until today using bottom fixed foundations. Source: Carbon Trust.

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[2] *Offshore innovation widens renewable energy options,* IRENA, Brief to G7 Policymakers, Sept. 2018. ISBN: 978-92-9260-079-2.

[3] BP Statistical Review of World Energy 2017.

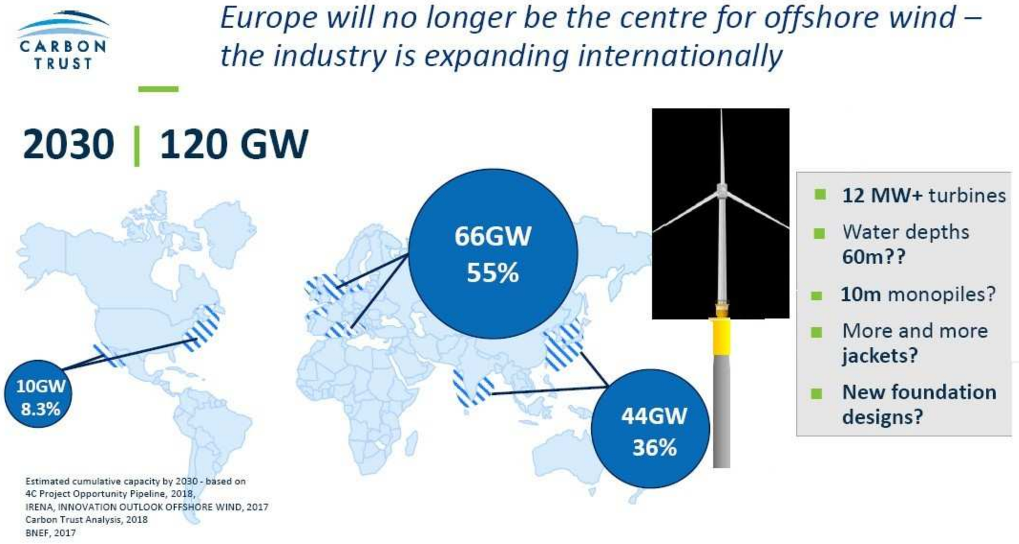

Fig. 3b. Expected installed capacities for 2030 showing changes in turbine and installation conditions. Source: Carbon Trust.

Similar to the 66 GW for European seas by 2030 in Fig. 3b, Wind Europe assumes 70 GW of offshore capacity installed in Europe in addition to 253 GW onshore [4].

In order to expand offshore wind's scope globally, enabling wind power to be cost efficiently developed also in deep water, floating solutions is a key requirement. Developers expect a significant fraction of the 2030 target capacity to be delivered by floating turbines. Estimates are typically 10 to 15 GW for 2030, *e.g.* by Equinor (formerly Statoil), French developer Eolfi, the UK's Carbon Trust, and various consultancies.

Floating wind turbines have been under demonstration at sea since 2008, with multi-turbine arrays are now coming on stream. The spar-buoy technology Hywind, owned by Equinor, is the most advanced, its *Hywind Scotland* 5 x 6-MW array at the Buchanan Deep, on stream since November 2017. Good production and high capacity factors have been reported. The WindFloat Atlantic project of EdP and partners is constructing a 24 MW array using semi-submersible *Windfloat* platforms to deploy in Portuguese waters from 2020. These two first floating arrays build on demonstrator units of 2.3 and 2.0 MW, respectively, tested at sea for several years. A second floating array off Scotland, *Kincardine,* has deployed one platform (the same 2MW demo unit used off Portugal), and is constructing further 5 units designed for 9.5 MW turbines with a total announced capacity of 50 MW. In France, four floating arrays of 24 to 25 MW each, one in the Atlantic and three in the Mediterranean, have been approved, a 2 MW turbine on the *Ideol* concrete barge is being tested at sea as a demonstrator. Japan has deployed and tested several floating demo units at sea using different technologies, and an array consisting of 11 concrete spar-buoy floaters is currently under construction by the company Toda. Around the world, more than a dozen technology developers are working to qualify alternate floating devices, with prototypes at various scale and maturity.

[4] Wind Energy in Europe: Scenarios for 2030, Wind Europe, September 2017.

W2Power is one of these emerging solutions. In development for more than a decade, its design is driven by the need for low cost, which it aims to achieve by innovative combination of proven technologies intended to de-risk floating wind. The semi-submersible W2Power platform supports a pair of wind turbines, enabling rated power per unit up to currently 12 MW, using 2 x 6 MW turbines that are commercially proven today. The platform has been optimised to maximise the MW power per mass of steel, which combined with the use of a pair of turbines and other features is intended to enable the lowest cost of energy of any floating wind system. Designed as a hybrid from its first conception, W2Power has space also for additional revenue-generating activities at sea to yield an upside economic potential.

As of June 2019, W2Power has reached TRL 6 by testing a fully functional prototype at sea following from a series of staged, well-documented wave-tank test campaigns. The present DemoWind project “WIP10+” includes design, engineering and construction of a seaworthy, fully-functional prototype, and testing of this 1:6 scale unit at sea to demonstrate the viability of the W2Power solution. This will enable moving on to larger scale demonstration projects from 2020 onwards. It is expected that the inherent de-risking advantages of W2Power will make it a serious contender for the global floating market.

Fig. 4. (Left): W2Power prototype installed at sea off Gran Canaria 17.06.2019, notice tug boat leaving in background. (Right): render of the full sized 12MW W2Power. Servicing vessel and large piece being lowered onto it shows scale.

Concurrently with technology demonstration, the DemoWind project studies application areas and environmental conditions for future W2Power floating wind parks. Characterising these is the purpose of the present study. This 2019 issue is an expanded and updated report compared to the first issue from 2017. Updates are provided for the overall potential and for countries and areas of primary interest and of the methodology used.

3. WIND RESOURCE IN DEEP WATER

3.1. Overview

The single most important driver for developing deepwater offshore wind is the availability of a stronger, more stable resource. However, data is surprisingly scarce for “just how good” a resource is, especially in terms of comparing areas, so problematic for our primary interest in this study, which is comparing countries with a view to identifying attractive exploitable areas around the world.

Very high wind resources and few competing uses are widely cited reasons for pushing offshore wind to deeper waters and investing in development of floating wind. However, poorly justified resource claims give planners and decision makers misleading information. Some commonly quoted numbers for this resource are: *(sources:* EWEA, NREL, Maine I.C.)

Europe	4000 GW	"80% of the offshore wind resource is in deep waters"
US	2450 GW	"60% in deep waters"
Japan	500 GW	"80% in deep waters"

In view of the fact that total world electricity generating capacity as of 2016 is 6390 GW [1], this can give the impression that resources will not limit the deployment of deepwater wind. This is by no means true: Any resource only has a value if it can be rationally exploited.

An illustrative breakdown of the US offshore wind resource potential is given in Fig. 5. The "technical resource potential" that results, of 2058 GW, is almost twice the installed power generation capacity of the US, 1074 GW as of 2016 [1]. As technologies are developed the economic potential will increase as cost of energy goes down with increasing mature.

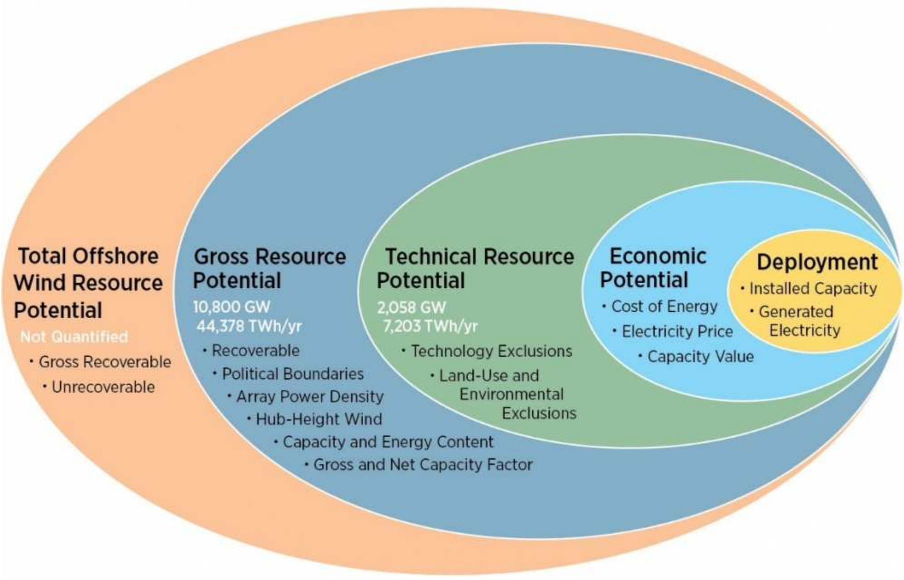

Fig. 5. Offshore wind resource potentials for the US [2].

Among the few attempts at quantifying wind resource quality is a study by NREL and DTU [3], which categorised the global wind resource into depth segments and higher- *vs.* lower-quality wind resource, using a simplified power curve method to assess capacity factors, *i.e.* the equivalent full load hours a generic turbine may achieve. This data set, more precisely, its embedded breakdown of *high-quality* wind resource, is the basis for the present analysis, which aims to achieve *well-justified* estimates for wind in deep water and get a more likely exploitation potential by area than a mere resource estimate.

In this analysis, geographical breakdown is by country and Exclusive Economic Zone (EEZ). One objective of this analysis is to eliminate irrational expectations of development potential based on resource alone. Another objective is to point out where development specifically of floating solutions might be the most natural choice, based on a deeper analysis.

Table 1: Countries with >100GW offshore wind resource by [3].

Rank		GW	of world
1	Russia	7268	11.9%
2	Australia	5449	8.9%
3	Canada	4884	8.0%
4	Norway	3635	6.0%
5	New Zealand	3423	5.6%
6	Argentina	3011	4.9%
7	Brazil	2969	4.9%
8	United Kingdom	2473	4.1%
9	Japan	2460	4.0%
10	China	2200	3.6%
11	United States (48)	2090	3.4%
12	Iceland	1459	2.4%
13	Indonesia	1401	2.3%
14	Mexico	1170	1.9%
15	Viet Nam	942	1.5%
16	South Africa	900	1.5%
17	Ireland	810	1.3%
18	France	749	1.2%
19	Taiwan	652	1.1%
20	Chile	642	1.1%
21	Venezuela	569	0.9%
22	Mozambique	510	0.8%
23	South Korea	501	0.8%
24	Papua New Guinea	498	0.8%
25	Sweden	420	0.7%
26	Western Sahara	410	0.7%
27	Honduras	382	0.6%
28	Bahamas	382	0.6%
29	Greece	368	0.6%
30	Uruguay	357	0.6%
31	New Caledonia	355	0.6%
32	Italy	343	0.6%
33	Somalia	331	0.5%
34	Nicaragua	323	0.5%
35	Spain	317	0.5%
36	Suriname	317	0.5%
37	Fiji	312	0.5%
38	Ukraine	310	0.5%
39	Mauritius	294	0.5%
40	Guyana	293	0.5%
41	Namibia	281	0.5%
42	Philippines	268	0.4%
43	Tunisia	266	0.4%
44	Netherlands	261	0.4%
45	Denmark	256	0.4%
46	Madagascar	248	0.4%
47	Morocco	244	0.4%
48	Portugal	169	0.3%
49	India	162	0.3%
50	Colombia	155	0.3%
51	Jamaica	141	0.2%
52	Trinidad and Tobagc	137	0.2%
53	Yemen	132	0.2%
54	Finland	131	0.2%
55	Cuba	130	0.2%
56	Romania	129	0.2%
57	Sri Lanka	126	0.2%
58	Germany	124	0.2%
59	Kenya	117	0.2%
60	Vanuatu	117	0.2%
61	Poland	114	0.2%
62	Latvia	105	0.2%

Table 1 (left) shows gross resource estimates as reported by NREL and DTU [3]. The 62 countries listed represent 98% of the world's total offshore wind resource, with the top 20 countries holding nearly 80%. The underlying data sets with our re-interpretation (see below) is given as Annex 2.

75% of total offshore wind resources are in deep waters at depths between 60 and 1000m [5]. Just 10% of the total is in shallow waters (<30m) and 15% at depths from 30 to 60m.

With a total resource 60 972 GW, nearly 10 times world current installed power generation capacity, the NREL-DTU study surely overestimates what might be even theoretically exploitable.

Fig. 6 shows the same gross estimate with a pie chart break-out for some countries with interests in offshore wind. The methodology used assigns large resources to countries with large sea areas but no special relevance: Russia, New Zealand or small island states with isolated power systems.

It is clear that a further assessment than quoting the NREL-DTU gross data is needed to get to an idea of which countries might be the most active in promoting floating wind power. With reference to Fig. 5 above, the scope is to define *accessible* offshore wind resource of high quality at relevant depth through a more in-depth analysis.

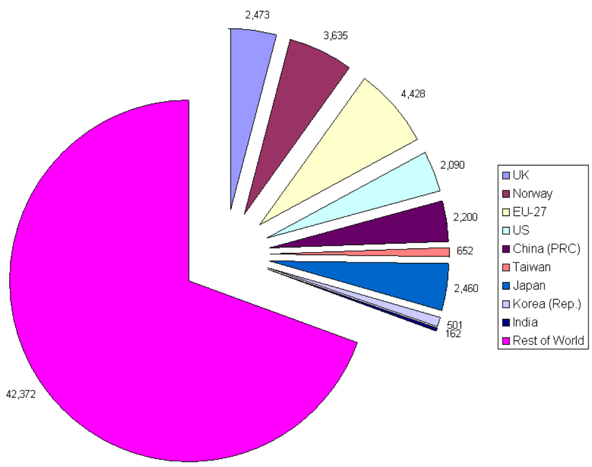

Fig. 6. Resource (GW) total for selected countries [3].

[5] Note: the depth cut off at 1000 m is in a sense arbitrary but can reasonably well be justified. Cases are known: Morro Bay (US Pacific) where floating arrays have been considered at 1000 m deep water.

3.2. Quality of resource and sea depth.

An interesting picture emerges when looking at the resource data by quality and depth range. The NREL-DTU data defines “high quality” (or high value) resource as sea areas where their generic 5 MW turbine achieves >46% equivalent full load hours. (Various other criteria could be used - the essential feature is high and consistent wind speed.) **Table 2** is a compilation of the Top 20 countries, in each depth range, when counting only high quality resources.

Table 2. Top 20 countries for high quality offshore wind resource: <30m, 30-60m, and >60m depth

Top 20: High-value resource in shallow waters.		GW	%
1	Brazil	200.5	15.9%
2	Australia	157.2	12.5%
3	Russia	138.2	11.0%
4	United Kingdom	114.0	9.0%
5	Netherlands	110.1	8.7%
6	China	96.3	7.6%
7	Denmark	64.4	5.1%
8	Venezuela	55.2	4.4%
9	Taiwan	44.7	3.5%
10	Canada	36.9	2.9%
11	Germany	27.5	2.2%
12	Argentina	25.9	2.1%
13	Viet Nam	25.6	2.0%
14	France	24.5	1.9%
15	New Zealand	24.3	1.9%
16	Colombia	18.7	1.5%
17	United States (48)	15.7	1.2%
18	Belgium	12.5	1.0%
19	Chile	11.5	0.0%
20	Madagascar	10.8	0.0%

Top 20: High-value resource at intermediate depth.		GW	%
1	Russia	586.5	13.3%
2	Australia	483.2	10.9%
3	United Kingdom	417.5	9.4%
4	Canada	223.6	5.1%
5	China	212.4	4.8%
6	Denmark	162.6	3.7%
7	Brazil	158.7	3.6%
8	Netherlands	150.9	3.4%
9	Norway	148.5	3.4%
10	Germany	96.8	2.2%
11	New Zealand	87.6	2.0%
12	Taiwan	69.0	1.6%
13	France	62.2	1.4%
14	Viet Nam	59.2	1.3%
15	United States (48)	49.2	1.1%
16	Argentina	48.8	1.1%
17	Mauritius	48.5	1.1%
18	Madagascar	34.3	0.8%
19	Ireland	34.3	0.8%
20	Chile	28.9	0.7%

Top 20: High-value deepwater wind.		GW	
1	Russia	3,817	14.9%
2	Canada	3,639	14.2%
3	Norway	3,350	13.1%
4	New Zealand	2,748	10.7%
5	Australia	1,842	7.2%
6	United Kingdom	1,841	7.2%
7	Iceland	1,440	5.6%
8	Japan	1,252	4.9%
9	Argentina	849	3.3%
10	Ireland	770	3.0%
11	South Africa	577	2.3%
12	Brazil	514	2.0%
13	Taiwan	499	1.9%
14	Chile	358	1.4%
15	France	310	1.2%
16	China	305	1.2%
17	United States (48)	248	1.0%
18	Mauritius	236	0.9%
19	Viet Nam	161	0.6%
20	Somalia	157	0.6%

The power of this more meaningful criterion is highlighted by the case of Germany: By gross data, the country that built the world’s 3rd largest offshore wind power sector barely makes it onto the resource ranking (in Table 1) at no. 54 of 62. Including resource quality, the German score becomes 11th and 10th in the shallow and the intermediate depth bracket respectively. This illustrates how misleading it can be to rely only on gross resource estimates: Germany’s sea space is not huge, it has no deep water, but all of its 124 GW is high quality resource.

Some observations by inspecting the listings in Table 2 compared to Table 1 stand out:

More than half of the global offshore wind resource is high quality.

Deepwater has the highest share of high quality wind resource whereas only 1/4 of the wind resource over shallow water is of high quality.

Differences between countries are very large. Generalisations in terms of “continents” (e.g. “Floating wind is very suitable for East Asia, but not for Europe”) are not meaningful.

Some countries have wind resources that are both very large and high quality. For example, Norway and Japan have >1000 GW resource, of which >95% is of high quality.

Also the UK, France, Canada, and Australia have very large resources of high quality.

The USA and China have large offshore resources, but a comparatively small fraction is high quality. The same applies for Vietnam, Brazil, Argentina and Venezuela.

Some large high quality resources are in low population countries with isolated power systems that limit the significance of development: Iceland, New Zealand, Mauritius.

Comparing countries in terms not only of total offshore resource and its depth but also its quality therefore gives new insight for exploitable areas. Since offshore developments always will carry higher costs than onshore wind, the portion of the resource of highest quality is always of most interest because it will generate the largest profit margin and justify major developments. Other criteria such as distance from shore and other climatic constraints (*e.g.,* strong waves) are secondary: As in all other energy industry, a large and high quality resource is the best driver for development.

Cumulating the listings of Table 2, Table 3 gives a Top 25 list of countries by cumulated high quality resources (at all depths), highlighting the percentage of high quality resource that is in deep water. (Note that the often larger deepwater resource dominates for many countries.)

3.3. Resource quality and depth: implications for some countries

Some countries have large, high quality offshore wind resources that may not be accessible. Two cases are Canada and Russia – circumpolar countries with huge, sparsely populated areas without a power grid. Russia also has a very low volume of wind power installations. Below a suggested "discounting" of resource for such lack of accessibility is given.

Table 3. Top 25 high quality resources.

	High value offshore wind World Top 25	GW		% in deep water
1	Russia	4,542	14.5%	84%
2	Canada	3,900	12.5%	93%
3	Norway	3,503	11.2%	96%
4	New Zealand	2,860	9.1%	96%
5	Australia	2,482	7.9%	74%
6	United Kingdom	2,372	7.6%	78%
7	Iceland	1,459	4.7%	99%
8	Japan	1,274	4.1%	98%
9	Argentina	924	3.0%	92%
10	Brazil	874	2.8%	59%
11	Ireland	810	2.6%	95%
12	China	614	2.0%	50%
13	Taiwan	613	2.0%	81%
14	South Africa	596	1.9%	97%
15	Chile	399	1.3%	90%
16	France	397	1.3%	78%
17	United States (48)	313	1.0%	79%
18	Mauritius	294	0.9%	80%
19	Netherlands	261	0.8%	0%
20	Denmark	248	0.8%	8%
21	Viet Nam	246	0.8%	66%
22	Madagascar	153	0.5%	70%
23	Venezuela	143	0.5%	51%
24	Colombia	133	0.4%	71%
25	Germany	124	0.4%	0%

	Spain	88	0.3%	90%
	South Korea	66	0.2%	
	Greece	35	0.1%	
	Barbados	16	0.1%	
	Belgium	16	0.1%	
	India	13	0.0%	
		29,766	95%	

At the other extreme are countries with well-developed offshore wind sectors and shallow seas: **Germany**, **Netherlands, Belgium** and **Denmark**. These have high quality resources in shallow waters, which are fully accessible and offering a potential for new (often larger) developments incorporating past ones. This represents a large and still-undeveloped potential for new wind farms on conventional fixed foundations in the already developed southern North Sea. Thus, these countries, which anyway have no deep water, will not play any major role in floating, except maybe via their strong maritime export industries (which see the EU as their home market).

France is seen from these data to have more high quality offshore resources than the four countries just mentioned, and it also exceeds the resource of the US. Accessibility is good in both the Atlantic and Mediterranean seas. The French resource is also well balanced, with more than half in each depth bracket of high quality. It represents 3 times France's current 129 GW generation capacity, today 77.5% nuclear, making France the world's largest exporter of electricity [6].

High quality offshore wind is attractive as a supplement to France's reliance on nuclear. 78% of its high quality wind is in deep water, so giving France substantial driving force to develop, without being as much "forced to go deep"

[6] World Nuclear Association, http://www.world-nuclear.org/information-library/

as some countries are (discussed in Sec. 3.5 below). However, the Mediterranean high quality resource lies only in deep water, while France's Atlantic and Channel coasts have wind resources of high quality located both in shallow, intermediate-depth and deep water.

The UK is very well endowed with high quality offshore wind resources across depth ranges. In shallow waters, 2/3 is high quality, and in deep water the UK resource is 78% high quality, a share equal to that of France. Scotland in particular has a very large high quality deepwater wind resource but little shallow water. A 2018 study [7] by ORE Catapult, commissioned by the Crown Estate office in Scotland found that the development of a a fully-fledged floating wind power sector in Britain could expand into a market worth almost £34bn (€40bn) by 2050 and create as many as 17,000 new jobs.

China (PRC) and the **United States** have the world's two largest national electricity systems, each with more than 1 TW installed power generating capacity on their national grids. China generated 6495 TWh electricity in 2017, up 6.7% from the previous year, while US power consumption declined slightly to 4282 TWh [8]. China produces and consumes more than ¼ of all electricity in the world. Interestingly, in this context, these heavyweights are exceptions to the trends observed when comparing "gross" *vs.* quality-adjusted offshore wind resource.

Whilst each has substantial offshore wind resources, "only" 30% of China's and 20% of the US resource [9] is high quality. Furthermore, the US and China both have abundant <u>on</u>shore resources in thinly-populated areas (the US Midwest, China's Northwest), the rather small land area fractions that have been developed there showing high turbine utilisation factors.

China has nearly 100GW of high quality resources in shallow water (such as in the intertidal zones north of Shanghai) that it has long been developing. Nationally, this may remain the priority, instead of a focus on deep water. Fig. 7 summarises offshore wind plans in coastal provinces, they sum to a pipeline of nearly 40 GW; though delayed, most of it still on-going.

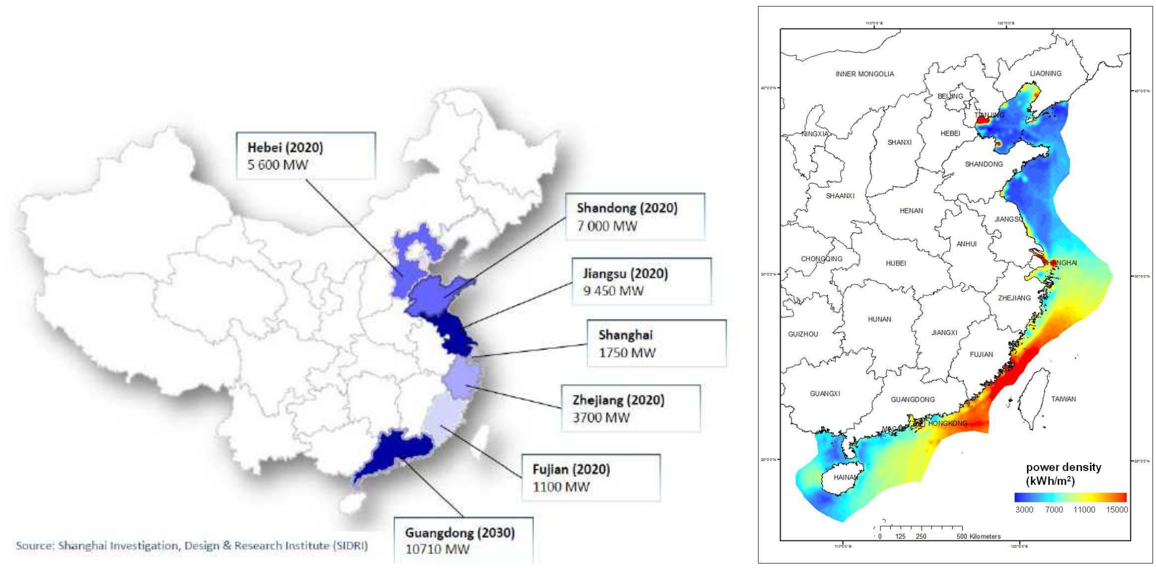

Fig. 7. Provincial plans for offshore wind power development, and (right) Coastal regions power density map. Sources: Innovation Norway 2013 and Aalborg University 2015-16.

[7] As reported in RECharge, 29 Octobe 2018

[8] BP Statistical Review of World Energy, 2017.

[9] US estimates in the NREL dataset are for the "lower 48" States only, Alaska and Hawaii forming part of the "Unclassified" resource.

Major coastal provinces such as Zhejiang, Guangdong and Fujian face ever greater power needs for their growing economies. This means that provinces that mostly have a deep water resource may take lead roles in developing these, even if national priorities are elsewhere. Currently [10], the southern Guangdong province which has both shallow and deep water is the most active and has secured that a number of its bottom-fixed projects of 400 MW to 1 GW will receive feed-in tariffs, otherwise to be replaced by auctions. Fujian previously was said to have developed plans for up to 2 GW floating wind development.

Concerning the US, as widely reported in industry press, it could develop “tens of GW” new offshore wind using fixed foundations and well-proven installation techniques in the shallow waters of the East Coast, where also some major load centers are located. The US is not at all “forced to go to deep” in order to become a major market for offshore wind. However, the differences between states are large, with strong states pursuing ambitious policies and the Pacific coast almost without any shallow water. Lead roles in developing floating wind power will be taken by individual states, not federally. The state of most interest is **California**.

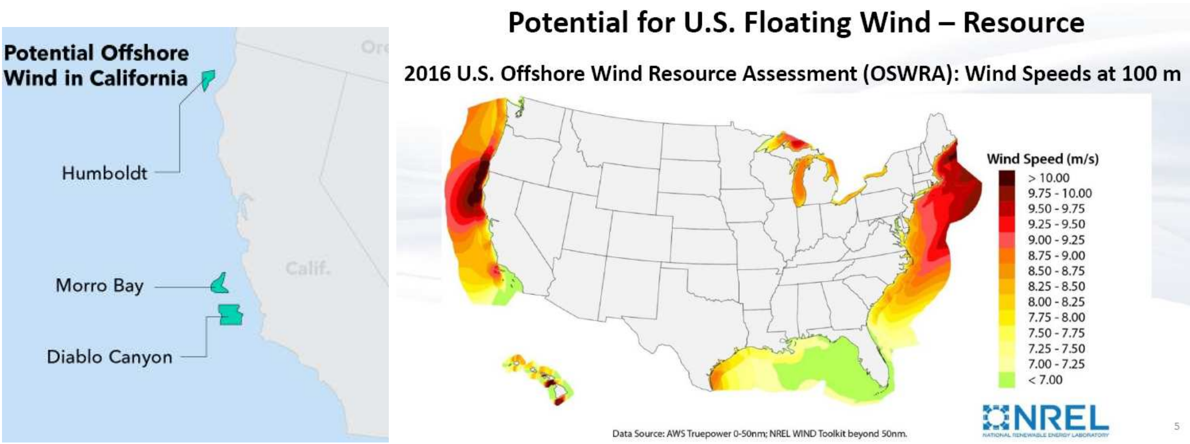

Fig. 8. (left) Planned offshore wind areas off California as of 2019 and (right) US offshore wind speed map. Source. BOEM.

The US’ by far most populous state is, in fact, often treated as a country by itself. California’s economy would be the world’s 5th largest if it were (and also the world’s largest net importer of electricity). A pioneer in renewables, both policy and technology, with 34% RES energy in 2018, California has high-quality offshore wind resources that entirely lie in deep water. The current status (April 2019) is that 14 companies submitted to the three Call Areas shown on the left figure, and BOEM (the federal agency in charge) is evaluating comments preparing a lease sale by a complex process. The floating wind turbines will be installed in waters from 200m to 1000m deep. On the East Coast, several leases have already been sold.

Some other countries. By comparing Tables 1, 2 and 3, some other countries with overall large resources (500 GW+) drop down the ranking when resource quality is included. In this group are Brazil, Argentina, Mexico and Venezuela, as well as Indonesia and Vietnam. It is natural for Brazil and Argentina with large, windy thinly-populated land areas, to develop on-shore first. Brazil is also top of the list for high quality wind in shallow water, more than its total generation capacity. Australia has a bigger resource than each of these, well distributed between depth categories, but also vast unpopulated land areas to consider developing.

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[10] Yuki Yu, “China’s ten biggest offshore wind projects”, REСharge 03.06.2019.

3.4. Corrections for Accessibility

As mentioned, two large countries skew the NREL/DTU data with huge resource estimates that are obviously not readily accessible, Canada and Russia. Much of their high quality wind resource is Arctic coastlines adjoining EEZ's with low population density and often no power grid. Thus, a heavy discount of the offshore wind resource should be applied in order to not distort the balance of resource estimates, by assigning too much resource to "Rest of World". There is good justification for discounting heavily each of these countries' resource.

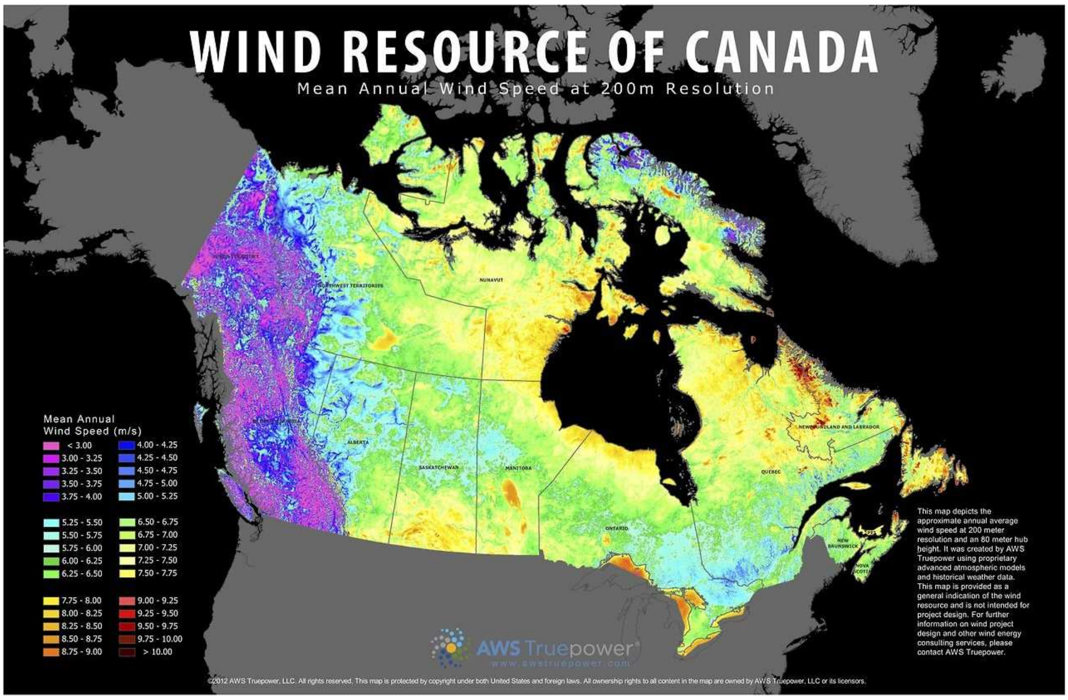

Fig. 9. Canada wind map (onshore), brown colour is high quality. *Source:* AWS Truepower.

For Canada an illustrative land based map is shown in Fig. 9. Extrapolating to adjoining seas (Great Lakes are outside the scope of the NREL/DTU data), it is clear that strong winds over deep-sea areas will be only in the far North-east.

Norway also shows a high resource and it has thinly populated areas in its North. However, the argument of being highly unrealistic to develop does *not* apply to it, because Norway's excellent resource is *not* confined to its remote areas. Fig. 10 shows that the strongest wind (annual mean speed >10.5 m/s) is in the south-west (North Sea, southern Norwegian Sea). Further, Norway has strong traditions in building (hydro) power stations at isolated locations, and developing grids as needed, which should apply equally to offshore wind.

The part beyond the Polar Circle does have a weaker grid and less resource quality; therefore a much milder discounting factor of 1/3 has been applied to the Norwegian deepwater wind resource.

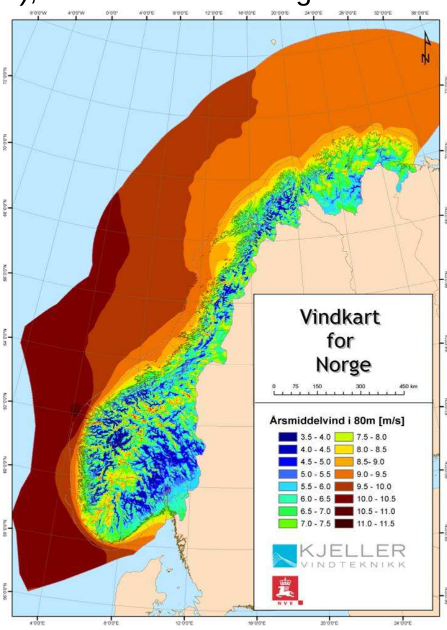

Fig. 10. Norway wind map, showing mean annual speeds on & offshore. *Source:* IFE.

Next, islands and isolated countries show up in NREL/DTU gross data with large resources. Examples are Iceland and New Zealand. While island markets are often useful as pilot sites, to include these at their full value in a realistic assessment of the global deepwater wind power economic potential would be misleading. These are small economies and energy systems. In contrast to Norway or Canada as discussed, such countries have no practical option nor nearby market they conceivably might export their electricity to other countries.

For these cases, the resource has been discounted to not overestimate the upper bound of potentially accessible deepwater wind resource. The % discount has been chosen so as to maintain around 50% offshore wind penetration for developed, but small/isolated economies (Iceland, NZ).

For developing countries like Mauritius, Madagascar and Barbados, and for Australia, some overload relative to today's power demand (also indicated in the data in Table 4) has been allowed taking into account future electricity market growth.

For a group of middle-income countries that also display quite high resource estimates, an intermediate-level discounting has been applied in order to limit their "unrealistic export" potential. This takes into account the limited electricity import capacity of their neighbouring countries for the foreseeable future (case of South Africa) as well as the mutually exclusive export potential for neighbouring countries (case of Chile / Argentina, Colombia / Venezuela).

Even if in normal economic times, it may be feasible for one of these country to develop an offshore wind industry that included export to the neighbour, this would not apply to both. In the latter cases the discounting factor used for the remaining resource estimate has been set to cover at least twice the current domestic (in-country) demand. A similar logic was applied to the case of Brazil, and to Vietnam for the case of its developing grid links with China.

Following the same logic, resource discounting has also been applied to Australia and, on a smaller scale, to Ireland. Ireland's huge, extremely windy sea area gives it correspondingly large resources that drown its small domestic power market (even as the "island of Ireland" power grid includes Northern Ireland a province of the UK). Discounting this as a resource is thus justified because the UK market, due to its own vast deepwater wind resource, is much less likely as an export target than the cases of Canada to US (even with its discounted wind resource base as per above) or that of Norway exporting to the EU. The small industrial base of Ireland and its significant shallow water wind resource are further limits.

The resultant corrected estimate of high-quality deepwater wind resource appears in Table 4. This data set is considered to be better suited for a more realistic assessment of resources and exploitation areas for W2Power and floating wind technologies in general. The resource discounting percentages are indicated. As a bonus, this correction methodology also gives a total resource estimate reduced from its obviously exaggerated value in excess of 25.000 GW to less than 8.000 GW. (though still much higher than world total power generation of 6390 GW – the sum in Table 4 excludes many smaller and landlocked countries.)

Table 4. Top 20 Countries for High quality wind energy resources in deep waters, GW.

	gross HQ GW's all depths	% of HQ in deep waters	apparent HQ GW's in deep waters	resource discount	corrected HQ GW's in deep waters	Total installed capacity, GW
1 Norway	3,503	96%	3,350.0	33%	2,234.5	33.9
2 UK	2,372	78%	1,840.9		1,840.9	94.6
3 Japan	1,274	98%	1,252.0		1,252.0	322.2
4 Taiwan	613	81%	498.9		498.9	48.6
5 France*	397	78%	310.4		310.4	129.3
6 China	614	50%	305.1		305.1	1646.0
7 US	313	79%	248.2		248.2	1074.0
8 Russia	4,542	84%	3,817.0	95%	190.9	263.5
9 Canada	3,900	93%	3,639.1	95%	182.0	150.3
10 Brazil	874	59%	514.5	75%	128.6	147.6
11 Australia	2,482	74%	1,841.9	95%	92.1	67.0
12 Spain*	88	90%	79.3		79.3	106.7
13 South Korea	66	99.8%	65.7		65.7	103.0
14 South Africa	596	97%	576.9	90%	57.7	47.3
15 Colombia	133	71%	93.9	50%	46.9	16.9
16 Argentina	924	92%	849.2	95%	42.5	36.5
17 Vietnam	246	66%	161.4	75%	40.3	45.4
18 Venezuela	143	51%	73.2	50%	36.6	32.2
19 Chile	399	90%	358.4	90%	35.8	22.0
20 Greece*	35	95%	33.0		33.0	18.9
* counted as "EU-27" in graphic				Sum top 25	7,776 GW	4,470 GW
Sum Top 20 + 5 by discounted deepwater HQ wind resource					GW	

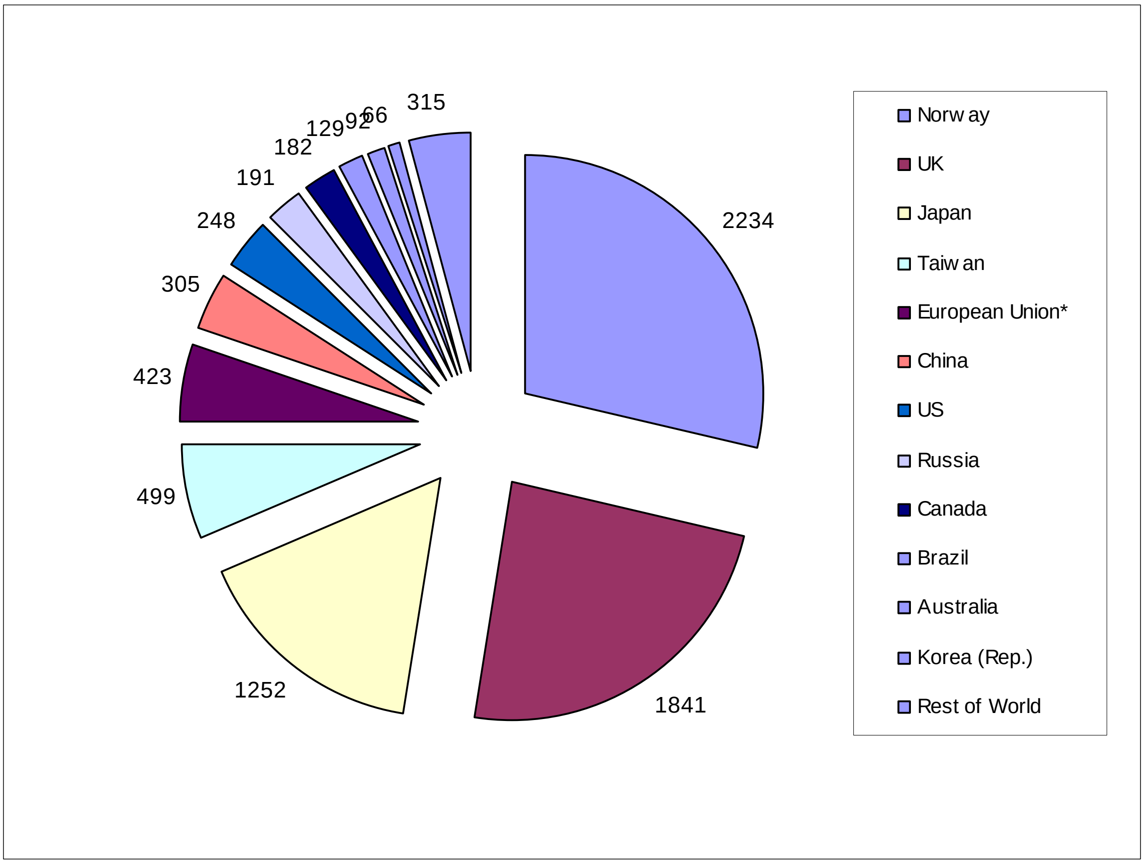

Fig. 11. Top 12 countries for accessible, high quality wind resource in deep waters, GW. (Note: "European Union" is the sum of the resource entries for France, Spain and Greece listed individually in Table 4)

Going back to the "much quoted" claims referred to on p. 7, we see that the figure 4000 GW for Europe is repeated and indeed exceeded in the processed data. However, of the nearly 4500 GW high-quality resouce, half is under the control of Norway and another 41% belongs to the UK. While Norway as an EEA member is well integrated in EU markets and applies EU policies in most domains, its energy situation is quite different from that of the EU. Only 10% of the "4000 GW" is with Member States of the post-Brexit EU-27, though this is in fact a very sizable resource: twice the combined offshore wind resources of Germany, the Netherlands, Belgium and Denmark in waters less than 30m deep. Furthermore, part of the EU deepwater resource is in the Mediterranean, motivating a push for floating wind power there.

The resource of **Japan** is also greater than the "rule of thumb" value 500 MW, at least before constraints such as Japan's important fisheries, sea lanes, protected nature areas etc. begin to be taken into account. However, for the US, while the overall claim of 2450 GW may hold, the 60% in deep water is clearly exaggerated when resource quality is taken into account as the number resultuing here is more like 10%.

3.5. Outlook for specific countries.

France defines its offshore wind development by the pluriannual national energy plan (PPE). Launched in November 2018, the 2019-28 PPE was criticised by some developers for low ambition, but France remains first in the world to plan commercial volumes of floating wind [11]. There will be two commercial tenders dedicated to floating: for Bretagne in 2021 (250 MW at 120€/MWh indicative price) and one for the Mediterranean in 2022 (250MW at €110/MWh). (Pricing for two larger bid rounds on fixed foundations are 70 and 65 €/MWh). Meanwile, the floating pilot arrays are going ahead with all permits to be in place in 2019 and power to grid from 2021. The PPE is structured with five to six years between the commissioning dates of the pilot and commercial farms to maximise learning and address any specific issues.

The overall timing is shown in Fig .12 and more details of the floating pilots in Fig. 13 and 14.

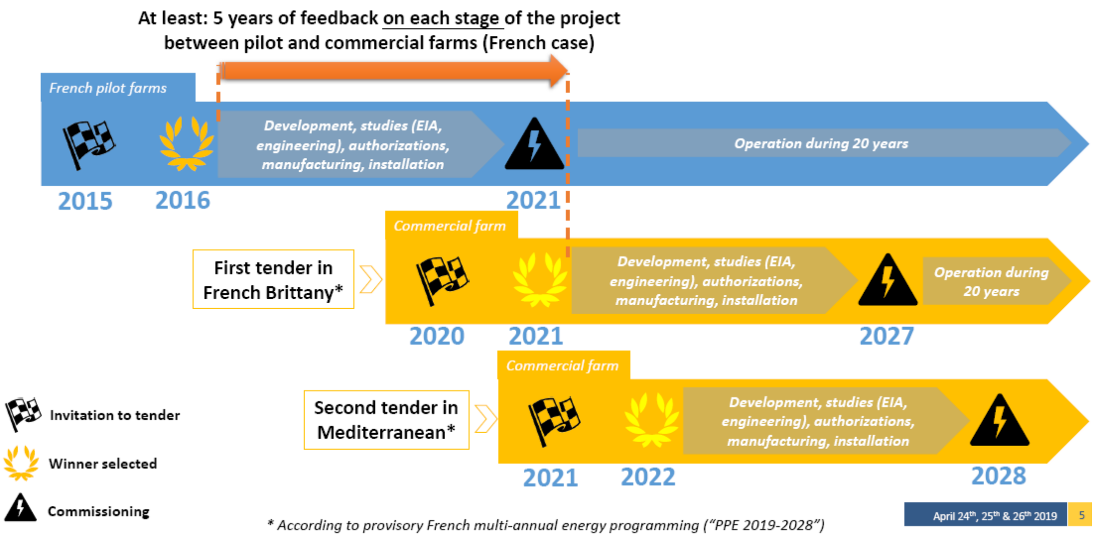

Fig. 12. Overview of the floating wind planning framework in France. Source: EOLFI.

[11] L. Michel, Ministry of Ecological Transition, presentation at FOWT-2019, Montpellier 24-26 April 2019.

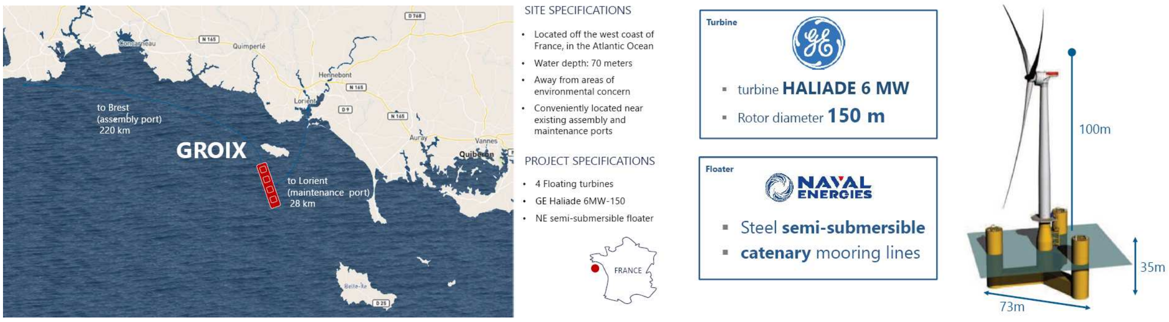

Fig. 13. The Ile de Groix pilot ("farm") floating array, with 4 x 6MW at 70 m depth, cost estimated at €200m. Source: EOLFI.

Fig. 14. (left) Mediterranean pilot farms locations and partners, (right): TLP structure (by SBM) chosen for the Provence Grand Large project at Faraman site, the only of the pilot to use 8MW turbines. Source: Pole Mer Mediterranée/EdF.

Some countries have deepwater as the only way to access large, high quality offshore wind resources with little or no potential for shallow water developments. The most prominent are **Norway** and **Japan**. These have massive resources of very high quality, sufficient to run its energy systems several times over, or in the case of Norway, to supply the EU-27 electricity markets with a large part of their electricity need, just as the country does today for gas.

High-quality wind resources located almost exclusively in deep water are also characteristics of **Spain, Korea**, **Greece** and the US state of **California**. Each has a high quality off-shore wind resource of similar magnitude as its total installed generation capacity, but almost no resource in shallow water. The dominance of deepwater in Korea is more pronounced than even Japan and Norway, approaching 100%. Table 5 shows key data for these 6 countries. Notice that, for all, less than 10% of high quality offshore wind resource is in shallow water.

Table 5. Countries whose offshore high quality wind resource is strongly dominated by deep water.

(all data in GW)	Norway	Japan	Korea	Spain	Greece	California
HQ offshore wind resource (Gross)	3503	1274	66	79	33	112
Resource in <30m water	<5	2	0	7	0	<3
Power generation capacity, total	33 or 113**	311	97	100	19	80
Onshore wind installed capacity, total *	1.7	3.7	1.2	23	2.4	6

Notes to Table 4: *GWEC, April 2019. **Norway is part of the Nord-Pool, of total installed capacity >113 GW, with 500-600 TWh/year traded across 6 borders (www.nordpoolspot.com). California data are from BOEM (2018).

These 6 countries, who by these criteria are “forced to go deep”, may be expected to take key or even leading roles in floating wind to access their valuable deep water wind resource. So is the EU: due to the fact that France, Spain and Greece are in this group with very high deep-water focus, a significant EU policy support drive for its development can be expected. Also, two EU countries with thriving wind power sectors, Portugal and Italy, have deep-water wind resources, but not of the high-quality class targeted by the present analysis. (For the case of Portugal, the upcoming Windfloat Atlantic array might provide results that are more promising than the resource data indicate.)

By analogy with its development in onshore wind, Italy can be considered as a likely second-phase adopter of floating wind technology, since its costs need to come further down in order to justify developing its lower-grade resource. Alternative solutions that may be available *vs.* the national targets committed will also play an important role, however.

Taiwan could justify a very active role due to its near 500 GW high quality resource in deep water. This zone is clearly seen on the map in Fig. 15. Taiwan, its government ambitiously reforming the power sector and aiming to replace a big part of its 42 GW generating capacity by renewables, solar and (mostly offshore) wind. Taiwan currently is the most active market in all offshore wind. More than 5.5 GW have been awarded by a mixture of feed-in tariff and auction processes, with large European developers such as Ørsted winning several.

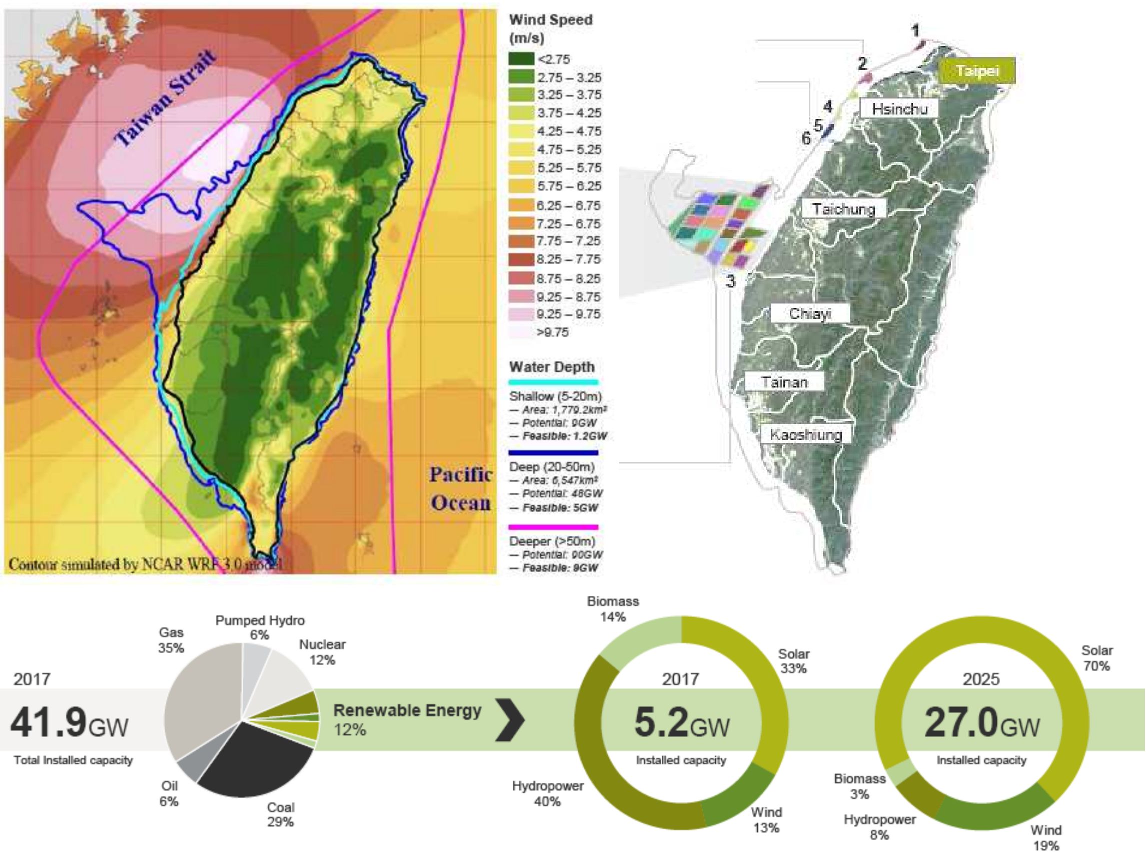

Fig. 15. Wind resource and depth chart, (top left), some already allocated areas and new power generation for Taiwan. Source: Green Investment group.

While of somewhat lower resource quality than Taiwan's, **Korea**'s offshore potential also is attracting developers and the government has announced ambitious plans. Some analysts point to a shallow water potential that might justify bottom-fixed development (at wind speeds of 6.5 to 7.5 m/s, thus far from being counted as "high quality" by our analysis.). See Fig. 16.

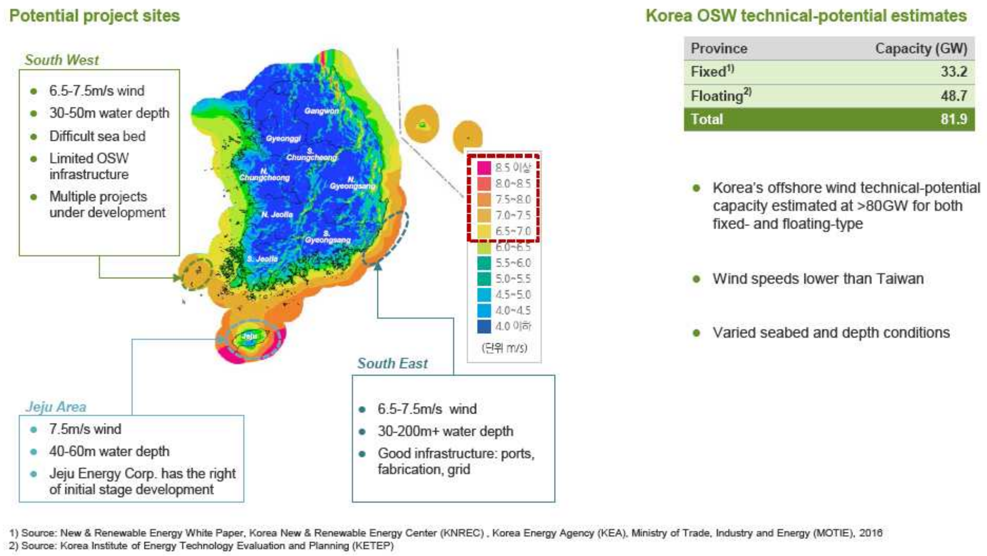

Fig. 16. Potential project areas and (independent) potential estimates for South Korea. Source: Green Investment Bank.

There are several uncertainities in planning, incentives and contract requirements that make progress in Korea so far slower than in Taiwan. According to recent reports, however, especially areas served from the major industrial and port city of Ulsan, on the east coast, might be proceeding faster than others [12].

Globally, the high quality offshore wind resource is well distributed so that developments may be expected also beyond the countries taking the lead. Countries such as **South Africa**, **Chile** and **Argentina** have large high quality deepwater resources, much in excess of their current total generating capacities. These countries should have incentives for adopting floating wind when their (also substantial) onshore potential has been realised. This may be sooner than one might expect at the rapidly dropping cost of on-shore wind energy today).

Among developed economies with large high quality wind resource New Zealand and Iceland are small electricity systems of less than 10GW total installed capacity far from all continental grids. Thus, alternative blue-sky options (…hydrogen…) would need to be imagined for any of these to become key promoters deepwater offshore wind. Also, their industrial base is limited. For Ireland, much would depend on export to the UK and possibly French markets.

The situation for North America and for "Greater China" is quite different, when a high quality resource falling under several jurisdictions is examined together. Canada (even discounted, as applied here) has a large high-quality wind resource that may complement the US one.

As seen above, the deepwater resource of small but highly developed Taiwan is significant also relative to the Mainland (PRC) market, and of very high quality. These cases all confirm that cross-border issues are highly relevant in the assessment of deepwater offshore wind.

[12] H. K. Shin, Towards the 1GW floating offshore wind farm Ulsan, Korea - presentation at FOWT-2019 Montpellier 24-26 April 2019.

For **Norway**, prospects for exporting vast amounts of electricity from high quality deep-water wind resources could influence the development perspective if its national priorities change. The country's offshore wind resource is relatively well characterised and several multi-GW offshore wind park areas have been sketched and partly planned [5].

Norway's electricity sector is already carbon free (hydropower) but Norway's oil & gas export and ambitious commitment under the Paris agreement might promote "unique" policy options that, on their own, would make little sense elsewhere. The Hywind Tampen project, 11 8-MW floating turbines to supply windpower to hydrocarbon facilities in an area of the North Sea known as Tampen is a case in point. See Fig. 17.

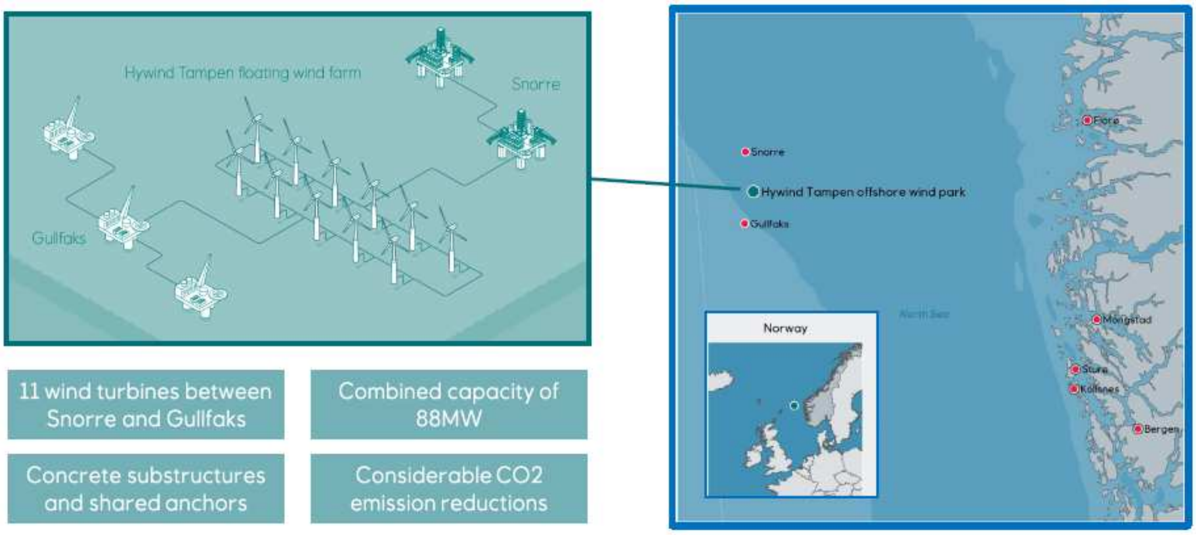

Fig. 17. The proposed Hywind Tampen 88 MW project: illustration and location in Norwegian North Sea. *Source:* Equinor.

The costs of Hywind Tampen, announced as NOK 5 billion, are lower per MW than the NOK 2 bn quoted for the Hywind Scotland 30 MW pilot array, by about 15% (NOK 56.8m/MW vs. NOK 66.7m/MW). Still, it corresponds to almost €5.9m / MW at current NOK exchange rates. Equinor has requested 50% co-funding from *Enova*, a national fund for energy efficiency, but the amount would consume the agency's entire annual budget. As of mid-2019 the FID (Final Investment Decision) for Hywind Tampen has been postponed to fourth quarter of 2019.

From 2005 to 2010, Norway was the world's leading promoter of floating wind with numerous independent technology developers[13]. Though not currently addressing the Norwegian power market, Equinor remains technology leader in floating with its spar-buoy technology, brought successfully to a TRL = 8 with the 30MW Hywind Scotland pilot array in November 2017. The company has also invested in and built several bottom-fixed offshore windfarms.

Very recently [14], it was announced that Equinor was interested in building a 200 MW floating wind park off the island of Gran Canaria. While some international media reported that there was already a permit given, the actual processing of the case is currently in the hands of the Spanish authorities. Spain previously (2012) placed a *de facto* moratorium on offshore wind developments in the wake of the economic crisis.

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[13] Indeed, also W2Power has Norwegian roots, through its precursor company and former developer Pelagic Power AS (est. 2005).
[14] "Equinor pide al Estado espacio para un parque eolico marino en las islas", 7Canarias newspaper, 01.06.2019.

4. CONCLUSIONS

The main conclusion on exploitation areas for deepwater wind is that a number of countries with high quality offshore wind resources could well justify a strong focus on the deepwater part of these:

The UK, Norway, Japan, Taiwan, Korea, the US, France and Greece (as well as Ireland) all have more than 75% of their high quality offshore wind resource in deepwater.

Countries with the highest resources in absolute numbers (Norway, Canada, Russia) have an even greater part of resources in deepwater. Russia is unlikely to be a lead developer but Norway and Canada might see export-driven initiatives vs. the adjoining EU and US markets.

Among big deepwater resource holders, exceptions to a deep-water focus are China, Brazil and Australia. They have large high quality resources in shallow waters as well.

Key countries for the market launch of deepwater wind are Japan, France and California. A major push for deep water needs at least one country's industry or market taking a leading position. For the UK, deepwater wind is one among several options, though Scotland has some of the best high quality deepwater resource in the world and limited shallow water.

In contrast to some other reports, this analysis indicates that deepwater wind is not likely to be driven primarily by market pull from the US or Chinese markets on their national levels, though California in the US and some coastal provinces of the PRC may very well take on leadership initiatives. The US and Chinese markets, both very large, will ultimately be open and important for floating wind, but may depend on other actors and countries breaking the cost barriers first. Currently, after Norway's Equinor, Japanese developers have the longest experience in terms of accomplishments, *i.e.* pilot demos at sea, but the highest activity in recent years has been in France. Several Regions in France are actively promoting "their" pilot arrays as a means of stimulating regional business.

Korea and Spain might also be positioned to be future leaders – not necessarily far behind Japan and France. Both have strong maritime industries and construction industry players, and Korea's world-leading role in building floating structures is a big advantage. Their high-quality offshore wind resources in deepwater are less than those of France and Japan, but could be more than sufficient to establish base markets from which industry could grow.

Norway has well qualified high-tech maritime industries, but is hampered by the reliance on oil & gas and resultant high cost in all sectors. Norway shares with Canada an abundance of low-cost hydropower in their power market, which structurally discourages all new renewable sources that will always cost more than hydropower. In addition to Equinor's global business, as well as that of Aker Solutions (part owner of Principle Power's Windfloat technology), the Norwegian maritime supply industry needs to mobilise in order to compensate for the lack of a home market for offshore wind so far. Norway could become a still more important mover, as might Canada, if the potential for major export of deepwater-wind-generated electricity to neighbouring markets, being respectively the EU & US, could be realised.

Taiwan is in an interesting position with greater deepwater high quality resources than in "mainland" China (PRC). Taiwan has a strong deep-water focus indicator and its market is comparable to Korea or Spain. It might even export power to the mainland, if cross-Straits politics improve.

In other parts of the world, there are good regional prospects, *e.g.* Chile, where a high-quality resource coexists with constraints on land and a fairly developed technology base. However, few countries in this category seem positioned to be world movers or leaders. Countries with huge resources - Brazil, Australia – face prioritising their challenges and have to their many other energy resources.

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[5]. *Havvind, Strategisk konsekvensutredning,* Report from Norwegian Water Resources Directorate last issue December 2012. In Norwegian.

[6.] California Renewable Energy Task Force, Bureau of Ocean Energy Management, www.boem.gov.

Annex 1: Power generation capacity by countries

Below are the most recent available data for total installed power generation capacity in GW.

1	China	1646
2	United States	1074
3	European Union	975
4	Japan	322
5	India	309
6	Russia	264
7	Germany	204
8	Brazil	150
9	Canada	148
10	France	129
11	Italy	117
12	Spain	107
13	Korea, South	103
14	United Kingdom	95
15	Turkey	73
16	Iran	73
17	Saudi Arabia	69
18	Australia	67
19	Mexico	65
20	Ukraine	57
21	Indonesia	55
22	Taiwan	49
23	South Africa	47
24	Vietnam	45
25	Thailand	41
26	Sweden	40
27	Egypt	39
28	Poland	37
29	Argentina	37
30	Netherlands	34
31	Norway	34
32	Malaysia	33
33	Venezuela	32
34	United Arab Emirat	29
35	Iraq	28
36	Austria	25
37	Romania	24
38	Pakistan	23
39	Philippines	23
40	Kazakhstan	22
41	Chile	22
42	Czechia	22
43	Belgium	21
44	Portugal	19.63
45	Switzerland	19.62
46	Greece	18.94
47	Israel	17.22
48	Algeria	17.12
49	Colombia	16.91
50	Finland	16.40
51	Kuwait	16.00
52	Denmark	14.01
53	Singapore	13.35
54	Uzbekistan	12.93
55	Bulgaria	12.70
56	Hong Kong	12.65
57	Peru	12.26
58	Bangladesh	11.84
59	Nigeria	10.48
60	Belarus	10.08
61	Korea, North	10.00
62	Syria	9.61
63	Ireland	9.56
64	Libya	9.46
65	New Zealand	9.28
66	Paraguay	8.87
67	Qatar	8.84
68	Hungary	8.47
69	Morocco	8.04
70	Oman	7.87
71	Serbia	7.59
72	Ecuador	7.44
73	Azerbaijan	7.42
74	Slovakia	7.11
75	Cuba	6.45
76	Puerto Rico	6.12
77	Tajikistan	5.50
78	Tunisia	5.03
79	Croatia	4.88
80	Burma	4.78
81	Laos	4.54
82	Uruguay	4.41
83	Jordan	4.38
84	Georgia	4.28
85	Bosnia and Herz.	4.24
86	Guatemala	4.07
87	Armenia	4.07
88	Sri Lanka	4.06
89	Turkmenistan	4.00
90	Bahrain	3.93
91	Kyrgyzstan	3.89
92	Ghana	3.80
93	Slovenia	3.74
94	Sudan	3.74
95	Dominican Rep.	3.73
96	Lithuania	3.64
97	Panama	3.20
98	Costa Rica	3.13
99	Moldova	3.00
100	Latvia	2.94
101	Iceland	2.77
102	Ethiopia	2.70
103	Congo, Dem. Rep.	2.62
104	Mozambique	2.56
105	Estonia	2.55
106	Honduras	2.50
107	Zambia	2.37
108	Lebanon	2.34
109	Kenya	2.25
110	Zimbabwe	2.13
111	Trinidad & Tobago	2.12
112	Macedonia	2.06
113	Luxembourg	2.02
114	Bolivia	1.99
115	Cote d'Ivoire	1.90
116	Albania	1.90
117	El Salvador	1.83
118	Cyprus	1.74
119	Angola	1.70
120	Bhutan	1.62
121	Kosovo	1.57
122	Cameroon	1.55
123	Cambodia	1.54
124	Yemen	1.53
125	Nicaragua	1.40
126	Tanzania	1.19
127	Mongolia	1.11
128	Mauritius	1.06
129	Nepal	0.97
130	Senegal	0.97
131	Uganda	0.92
132	Jamaica	0.90
133	Brunei	0.84
134	Guinea	0.74
135	Gabon	0.67
136	Malta	0.67
137	Madagascar	0.67
138	Afghanistan	0.60
139	Papua New Guinea	0.60
140	Mali	0.59
141	Bahamas	0.58
142	New Caledonia	0.56
143	Guam	0.55
144	Congo, Rep.	0.55
145	Andorra	0.520
146	Namibia	0.514
147	Macau	0.472
148	Guyana	0.438
149	Suriname	0.435
150	Mauritania	0.412
151	Malawi	0.373
152	Equatorial Guinea	0.334
153	Fiji	0.333
154	Virgin Islands	0.316
155	Haiti	0.313
156	Burkina Faso	0.306
157	Aruba	0.296
158	Eswatini	0.281
159	Barbados	0.267
160	French Polynesia	0.249
161	Togo	0.229
162	Benin	0.213
163	Montenegro	0.192
164	Belize	0.191
165	Greenland	0.187
166	Niger	0.179
167	Bermuda	0.171
168	Cabo Verde	0.158
169	West Bank	0.152
170	Rwanda	0.152
171	Eritrea	0.141
172	Botswana	0.134
173	Cayman Islands	0.132
174	Djibouti	0.130
175	Faroe Islands	0.128
176	Liberia	0.125
177	Gambia	0.114
178	Maldives	0.104
179	Saint Lucia	0.089
180	Seychelles	0.087
181	Antigua and Barbu	0.087
182	Somalia	0.081
183	Sierra Leone	0.081
184	Lesotho	0.080
185	South Sudan	0.080
186	Turks and Caicos I	0.079
187	Burundi	0.068
188	St Kitts and Nevis	0.063
189	Western Sahara	0.058
190	Marshall Islands	0.052
191	Grenada	0.050
192	St Vincent and the	0.048
193	British Virgin Islanc	0.048
194	Chad	0.047
195	Samoa	0.045
196	Central African Re|	0.044
197	Gibraltar	0.043
198	American Samoa	0.041
199	Solomon Islands	0.037
200	Dominica	0.033
201	Vanuatu	0.033
202	Guinea-Bissau	0.028
203	St. Pierre and Miqu	0.028
204	Comoros	0.026
205	Sao Tome and Prir	0.020
206	Micronesia, Federa	0.018
207	Tonga	0.017
208	Cook Islands	0.010
209	Falkland Islands	0.010
210	Kiribati	0.008
211	Saint Helena, Asce	0.008
212	Tuvalu	0.005
213	Nauru	0.005
214	Montserrat	0.005
215	Niue	0.001
	all 214 countries - EU	**6390**

Source: CIA World Energy Factbook, most data from 2016 (some are 2015 estimates)

6. Annex 2: Indicators developed

The analysis allowed a ranking of countries' offshore wind resources by depth and quality. We could achieve a ranking by high quality offshore wind resource for deep waters.

An important purpose of this study was to search for consistent predictions for what countries might be the most active and/or first to develop its deep water wind resource, necessarily by floating technology. To assist with selecting, a set of secondary indicators was introduced to help in ascertaining the importance of the resource, especially in deep water. Such indicators could be defined in response to the following three questions:

1. How **"important"** could high quality offshore wind be in a country's energy system?

2. How **"urgent"** is moving to offshore, in view of developed on-shore wind resources?

3. How much of the sought-after high quality resource exists **in deepwater**?

The indicators corresponding to these three questions together will allow identifying countries most favoured for deepwater offshore wind developments.

The "Importance" indicator I1:

I1 = high quality offshore wind resource / total power generation capacity

The "Urgency" indicator I2:

I2 = high quality offshore wind resource / onshore wind already installed

The "Deepwater Focus" indicator I3:

I3 = fraction of high quality resource in deep water, taking into account I1 and I2

Some values for the three indicators are given in Table A1 and commented below.

Table A1. Top countries with high quality offshore wind resource and calculated values for Indicators I1, I2 and I3. (Data for onshore wind are 2016, source: GWEC). Note – total GW and onshore wind GW not updated from v1.1.

	high-value wind GW	total GW installed	on-shore wind GW	I1	I2	I3
Russia	4,542	226.4	0.1	20.06	45417	**84%**
Canada	3,900	145.8	11.9	26.74	328	**93%**
Norway	3,503	32.8	0.9	106.94	3893	**96%**
Australia	2,482	62.3	4.3	39.84	577	**74%**
United Kingdom	2,372	85.6	14.5	27.71	164	**78%**
Japan	1,274	311.4	3.2	4.09	398	**98%**
Argentina	924	36.6	0.3	25.23	3080	**92%**
Brazil	874	128.7	10.7	6.79	82	**59%**
Ireland	810	4.7	2.8	171.90	289	**95%**
China	614	1,223.4	169.0	0.50	4	**50%**
Taiwan	613	48.4	0.7	12.67	875	**81%**
South Africa	596	46.0	1.5	12.96	397	**97%**
Chile	399	18.9	1.4	21.12	285	**90%**
France	397	124.0	12.1	3.20	33	**78%**
United States (48)	313	1,039.0	82.2	0.30	4	**79%**
Netherlands	261	26.6	4.3	9.82	61	**0%**
Denmark	248	14.5	5.2	17.12	48	**8%**
Germany	124	153.0	50.0	0.81	2	**0%**

Comments on I1, the “Importance” indicator:

This ratio illustrates how important is high quality offshore wind in a country's energy system.

Japan, France, Australia (and the Netherlands, for shallow water) could easily cover more than their energy need from high-quality offshore wind alone. US and China (and Germany for shallow water) could get up to 30-60% of their current electricity generation needs from this clean source.

This ratio can also tell if high quality offshore wind resources are an export proposition. Countries with a lot of high quality offshore wind <u>and</u> within a continental power system would see export potential. Notable examples are Norway and Canada. Canada may see electricity export opportunities to the US, Norway (and theoretically Russia) could see the same to the EU-27, and in a better political situation, so could perhaps Taiwan to the PRC.

The I1 indicator could also be used as a "sufficiency" indicator: How much of a country's high-quality resource does it need to develop to reach goals?

A case in point is Japan: it would need to develop only (1/4.1) = 24% of its high quality wind resource offshore to match its current total generation capacity. However, the US – even if the unlikely case of developing all of its high-quality resource – could "only" reach 1/3 of current installed capacity.

Comments on I2, the "Urgency" indicator:

The ratio of offshore high quality wind potential to already installed onshore wind tells about the "urgency" of accessing new resources.

Countries that already have installed a high onshore wind capacity would see going offshore as more urgent than countries who are just starting up with onshore wind farms.

- The low value for USA, China, France (and DE/DK/NL for shallow water) indicates this.
- The UK in this respect falls in an intermediate group together with Japan and Brazil
- Some countries with >1000 scores for this indicator and large, unpopulated land area (Russia, Argentina, Australia) might choose to develop their onshore wind resources first. Others (Chile, Taiwan) may have local limits (earthquakes, typhoons) favouring offshore.

Comments on I3:

This is less of an indicator than I1 and I2 as it does not capture resource size. As seen in the analysis of individual countries, there is a challenge to identify countries “forced to go deep”, not merely “forced to go offshore” for developing wind power. Clearly this is a subject that could be further explored, but it was not required for the very clear cut case of identifying the six “Forced to go deep” countries. In addition to resources, alternatives (perceived or real) in terms of low-carbon energy would need to be taken into account. The value chain of floating wind is different from that of fixed foundation developments, more like the maritime (formerly shipbuilding) industry, so parameters related to industrial structure might be drawn upon. It is interesting to note that France, Norway, Spain, Japan and Korea all have sizeable maritime construction sectors which could be taken into account in developing floating wind.

7. Annex 3: Data tables.

Resource classification for offshore wind by country, sea depth, and wind resource quality approximated by estimated capacity factors (% of totally available full load hours). Data first published by NREL and DTU [3], re-organised and re-interpreted by 1-Tech ©2012-2019.

Data compiled and edited from NREL TP-6A20-55049 "Improved offshore wind resource assessment in global..."

Global offshore wind resource potential GW — **With new analysis by 1-Tech**

SHEET 1	**SHALLOW WATER 0-30 m**				Total GW	**MEDIUM DEEP 30-60 m**				Total GW	**DEEP WATER 60-1000 m**				Total GW	**Total GW**		High quality resource	
!! est. capacity factor	34-38%	38-42%	42-46%	>46%	Shallow	34-38%	38-42%	42-46%	>46%	Interm.	34-38%	38-42%	42-46%	>46%	Deep	offshore	%	GW	% of all
Albania	0	0	0	0	0	0.02	0	0	0	0.02	13.1	14.78	0	0	27.88	27.90	0.0%		
Algeria	0	0	0	0	0	0.08	0	0	0	0.08	5.18	0	0	0	5.18	5.26	0.0%		
Angola	0	0	0.02	0	0.02	0	0.66	0.48	0	1.14	0	7.52	16.86	1.18	25.56	26.72	0.0%		
Argentina	2.34	47.6	220.6	**25.94**	296.48	3.6	74.26	385	**48.82**	511.68	44.28	255.56	1,053.60	**849.22**	2,202.60	3,010.80	**4.9%**	**924**	**3.1%**
Australia	159.02	257.74	268.1	**157.2**	842.06	94.2	342.56	309.26	**483.24**	1229.3	80.88	255.38	1,199.10	**1841.9**	3,377.30	5,448.60	**8.9%**	**2,482**	**8.3%**
Bahamas	90.36	36	0.06	0	126.42	4.14	5.28	0.02	0	9.44	99.62	137.3	9.26	0	246.18	382.04	0.6%		
Barbados	0	0	0	0	0	0	0	0	0	0	0	0	0.14	16.40	16.54	16.54	0.0%	**16**	**0.1%**
Belgium	0	0	0	**12.48**	12.48	0	0	0	3.18	3.18	0	0	0	0	0.00	15.66	0.0%	**16**	**0.1%**
Belize	0	2.8	0.66	0.04	3.5	0	0.06	0.12	0	0.18	0	3.02	9.5	0	12.52	16.20	0.0%		
Brazil	34.4	197.66	481.12	**200.52**	913.7	21.16	152.62	373.72	**158.72**	706.22	193.32	333.94	307.28	**514.46**	1,349	2,968.90	**4.9%**	**874**	**2.9%**
Bulgaria	1.4	0	0	0	1.4	5.74	0.54	0	0	6.28	27.02	1.36	0	0	28.38	36.06	0.1%		
Cameroon	0.58	0	0	0	0.58	0	0	0	0	0	0	0	0	0	0	0.58	0.0%		
Canada	0.1	1.2	9.44	**36.94**	47.68	2.06	9.74	85.58	**223.64**	321.02	17.42	329.2	529.98	**3639.1**	4,515.70	4,884.40	**8.0%**	**3,900**	**13.1%**
Cape Verde	0	0.62	0	0	0.62	0	1.76	0.02	0	1.78	0.12	21.72	1.6	0	23.44	25.84	0.0%		
Chile	0	0.00	1.32	11.52	12.84	0	0.18	5.78	28.86	34.82	6.42	59.10	170	**358**	594	641.82	1.1%	**399**	**1.3%**
China	71.86	116.68	31.42	**96.30**	316.26	76.20	318.28	149.54	**212.42**	756	55.12	202.30	565	**305**	1,127	2,199.80	**3.6%**	**614**	**2.1%**
Colombia	0.26	0.04	0	**18.66**	18.96	1.16	0.26	0.02	19.98	21.42	7.66	8.5	4.20	**93.86**	114	154.60	0.3%	**133**	**0.4%**
Costa Rica	0	0	0.1	0.00	0.1	0.00	0.00	0.14	0	0.14	4.16	15.78	7.66	0	27.6	27.84	0.0%		
Croatia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.0%		
Cuba	29.28	11.18	0	0	40.46	1.94	0.92	0	0	2.86	48.78	34.24	3.22	0	86.24	129.56	0.2%		
Denmark	0	0	0	**64.44**	64.44	0	0	0.98	**162.56**	163.54	0	0	7.04	20.84	27.88	255.86	0.4%	**248**	**0.8%**
Dominican Republic	0	0.06	18.72	0.18	18.96	0	0.08	1.5	0.02	1.6	0	2.32	41.26	8.54	52.12	72.68	0.1%		
Ecuador	0.3	0	0	0	0.3	1.26	0	0	0	1.26	0.16	0	0	0	0.16	1.72	0.0%		
Egypt	0	0	0.38	0	0.38	0	0	0.32	0	0.32	19.2	35.72	16.52	0	71.44	72.14	0.1%		
Eritrea	0.1	0.78	0.44	0	1.32	3.04	12.46	0.74	0	16.24	3.18	12.78	0.78	0	16.74	34.30	0.1%		
Estonia	0	0	3.94	0	3.94	0	0	15.12	0	15.12	0	0	31.38	0	31.38	50.44	0.1%		
Fiji	1.84	22.22	11.68	0	35.74	1.06	16.88	9.38	0	27.32	0.08	98.8	149.9	0	248.78	311.84	0.5%		
Finland	0	0.3	4.48	1.52	6.3	0	2.00	24.64	2.74	29.38	0	5.18	90.18	0.24	95.6	131.28	0.2%		
France	0	4.48	17.4	**24.54**	46.42	0	25.84	46.72	**62.16**	134.72	2.78	49.08	205.84	**310.38**	568.08	749.22	1.2%	**397**	**1.3%**
French Polynesia	0.2	1.54	0.98	0	2.72	0.14	0.46	0.76	0	1.36	5.12	39.86	14.64	0.84	60.46	64.54	0.1%		
Germany	0	0	0	**27.54**	27.54	0	0	0	**96.8**	96.8	0	0	0	0	0	124.34	0.2%	**124**	**0.4%**
Greece	0	0	0.1	0	0.1	0.1	0	0.02	1.76	1.88	51.8	116.5	164.36	33.02	365.68	367.66	0.6%	**35**	**0.1%**
Guadeloupe and Martir	0	0	0.02	0.06	0.08	0	0	0.1	0.5	0.6	0	0	19.98	7.18	27.16	27.84	0.0%		
Guatemala	0	0.64	0	0	0.64	0.00	0.14	0	0	0.14	0	0.78	0	0	0.78	1.56	0.0%		
Guyana	46.52	55.7	0	0	102.22	0.94	105.46	0	0	106.4	0	82.22	1.9	0	84.12	292.74	0.5%		
Haiti	0	0.72	0	0	0.72	0	0.14	0	0	0.14	0	4.86	4.54	0.48	9.88	10.74	0.0%		
Honduras	0	7.44	141.84	0.68	149.96	0	1.06	61.12	0.68	62.86	0	12.64	156.6	0.06	169.3	382.12	0.6%		
Iceland	0	0	0	1.52	1.52	0	0	0	17.9	17.9	0	0	0	**1,440.00**	1,440.00	1,459.40	2.4%	**1,459**	**4.9%**
India	9.6	11.6	13.06	3.6	37.86	10.56	3.86	15.58	5.72	35.72	29.04	18.2	36.82	3.98	88.04	161.62	0.3%	**13**	**0.0%**
Indonesia	70.08	120.92	268.08	0	459.08	75.88	240.52	7.82	0	324.22	276.82	321.06	19.9	0	617.78	1,401.10	2.3%		
Ireland	0	0	0	5.1	5.1	0	0	0	**34.28**	34.28	0	0	0	**770.28**	770.28	809.66	1.3%	**810**	**2.7%**
Italy	0	0.2	0	0	0.2	1.2	2.9	0	0	4.1	188.34	150.2	0	0	338.54	342.84	0.6%		
Jamaica	0	11.44	22.68	4.56	38.68	0	2.26	4.1	1.24	7.6	0.68	38.92	36.02	18.64	94.26	140.54	0.2%		
Japan	1.48	0.48	1.22	2.24	5.42	2.16	8.56	8.68	19.46	38.86	31.64	189.9	941.74	**1,252.00**	2,415.20	2,459.50	**4.0%**	**1,274**	**4.3%**
Kenya	0	2.12	0	0	2.12	0	1.9	0	0	1.9	13.66	99.4	0	0	113.06	117.08	0.2%		
Latvia	0	0	10.08	0	10.08	0	0	33.46	0	33.46	0	0	61.38	0	61.38	104.92	0.2%		
Libya	0	0.06	0	0	0.06	0.62	0.82	0	0	1.44	13.4	12.68	0	0	26.08	27.58	0.0%		
Lithuania	0	0	1.04	0	1.04	0	0.08	14.94	0	15.02	0	0	10.9	0	10.9	26.96	0.0%		
Madagascar	2.82	2.46	1.42	10.82	17.52	8.36	14.74	1.8	34.34	59.24	8.18	41.12	14.08	107.68	171.06	247.82	0.4%	**153**	**0.5%**

Data compiled and edited from NREL TP-5A20-55049 Improved offshore wind resource assessment in global...

Global offshore wind resource potential GW

With new analysis by 1-Tech

SHEET 1	SHALLOW WATER 0-30 m				Total GW	MEDIUM DEEP 30-60 m				Total GW	DEEP WATER 60-1000 m				Total GW	Total GW		High quality resource	
!! est. capacity factor	34-38%	38-42%	42-46%	>46%	Shallow	34-38%	38-42%	42-46%	>46%	Interm.	34-38%	38-42%	42-46%	>46%	Deep	offshore	%	GW	% of all
Malta	0	0	0	0	0	0	0	0	0	0	39.7	0	0	0	39.7	39.70	0.1%		
Mauritania	15.32	0.48	0	0	15.8	1.8	0	0	0	1.8	12.06	0.8	0	0	12.86	30.46	0.0%		
Mauritius	0	0	0	8.84	8.84	0	0	0	**48.46**	48.46	0	0	0.14	236.26	236.4	293.70	0.5%	294	1.0%
Mexico	64.16	130.02	3.4	0.66	198.24	82.74	279.44	7.1	3.22	372.5	193.34	290.88	105.98	8.54	598.74	1,169.50	1.9%		
Morocco	0.06	0.52	0.64	0	1.22	15.06	11.94	5.1	0	32.1	65.88	92.4	51.96	0	210.24	243.56	0.4%		
Mozambique	28.88	1.26	2.76	0	32.9	79.68	2.48	10.48	0	92.64	83	73.64	209.18	18.6	384.42	509.96	0.8%		
Namibia	0	0	0	0	0	0.02	0.02	0.16	0	0.2	58.7	130.2	89.92	1.56	280.38	280.58	0.5%		
Netherlands	0	0	0	**110.14**	110.14	0	0	0	**150.9**	150.9	0	0	0	0.04	0.04	261.08	0.4%	261	0.9%
Netherlands Antilles	0	0	0	0.02	0.02	0	0	0	0.98	0.98	0	0	0	27.14	27.14	28.14	0.0%		
New Caledonia	0	0.06	19.86	0	19.92	0	0.06	36.26	0	36.32	0	1	297.76	0.46	299.22	355.46	0.6%		
New Zealand	2.94	6.9	1.24	**24.32**	35.4	7.44	14.3	7.86	**87.64**	117.24	33.44	131.16	357.34	**2,748.10**	3,270.10	3,422.70	5.6%	2,860	9.6%
Nicaragua	6.04	27.02	167.96	0	201.02	7.84	5.22	11.26	0	24.32	14.52	42.28	39.66	1.42	97.88	323.22	0.5%		
Nigeria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.0%		
North Korea	0.96	0	0	0	0.96	9.48	0	0	0	9.48	14.86	0	0	0	14.86	25.30	0.0%		
Northern Mariana Islan	0	0	0.98	0	0.98	0	0	0.3	0	0.3	0	0	26.16	0	26.16	27.44	0.0%		
Norway	0	0	0.46	4.96	5.42	0	0.3	14.54	**148.46**	163.3	0.72	15.86	99.44	**3,350.00**	3,466.00	3,634.80	6.0%	3,503	11.8%
Oman	0.06	0.3	0.02	0	0.38	0.26	2.26	0.02	0	2.54	2.7	5.8	0.14	0	8.64	11.56	0.0%		
Panama	0.28	0.38	0	0	0.66	0.22	0.98	0	0	1.2	5.9	4.1	0	0	10	11.86	0.0%		
Papua New Guinea	10.82	102.48	93.64	1.24	208.18	11.22	33.64	3.18	0.02	48.06	55.38	149.56	36.12	0.96	242.02	498.26	0.8%		
Peru	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0.02	0.02	0.0%		
Philippines	3.92	30.24	0.68	0.16	35	0.62	22.8	0.86	0.42	24.7	12.28	91.8	32.42	71.46	207.96	267.66	0.4%		
Poland	0.96	0.02	12.66	0	13.64	0	0	32.28	0	32.28	0	0	67.84	0	67.84	113.76	0.2%		
Portugal	0	0.12	0.54	0	0.66	0	7.18	4.14	0	11.32	17.04	26.36	113.86	0	157.26	169.24	0.3%		
Puerto Rico and U.S. V	0	0	1.7	0	1.7	0	0	3.1	0.18	3.28	0	0	37.38	4.1	41.48	46.46	0.1%		
Reunion	0	0	0.22	0	0.22	0	0	0.16	0	0.16	0	0	0.9	1.38	2.28	2.66	0.0%		
Romania	2.82	0	0	0	2.82	27.62	19.72	0	0	47.34	4.86	74.08	0	0	78.94	129.10	0.2%		
Russia	7.3	70.9	47.6	**138.22**	264.02	30.48	90.8	164.52	**586.46**	872.26	217.62	622.48	1,474.90	**3,817**	6,132.00	7,268.30	11.9%	4,542	15.3%
Samoa	0	0	0.02	0	0.02	0	0.04	0.08	0	0.12	0	5	2.98	0	7.98	8.12	0.0%		
Saudi Arabia	0	0	0	0	0	0	0	0	0	0	15.06	21.3	0	0	36.36	36.36	0.1%		
Solomon Islands	0.04	2.1	1.24	0	3.38	0.02	1.54	0.42	0	1.98	22.6	36.68	7.26	0	66.54	71.90	0.1%		
Somalia	0	0	0.42	0.92	1.34	0	0	7.98	19.08	27.06	4.84	70.42	70.3	157.02	302.58	330.98	0.5%		
South Africa	0.12	0.02	0	1.28	1.42	0.18	1.2	0.64	17.5	19.52	46.54	111.8	143.48	**576.94**	878.76	899.70	1.5%	596	2.0%
South Korea	0.14	0.36	1.46	0	1.96	25.56	33.06	9.94	0.14	68.7	44.9	129.8	190.26	65.7	430.66	501.32	0.8%	66	0.2%
Spain	3.04	8.08	3.22	7.02	21.36	2.3	4.22	1.98	1.42	9.92	100.94	77.88	27.68	79.34	285.84	317.12	0.5%	88	0.3%
Sri Lanka	9.22	12.9	11.86	2	35.98	4.58	13.38	3.68	2.68	24.32	13.12	19.48	27.38	5.9	65.88	126.18	0.2%		
Suriname	61.08	2.96	0	0	64.04	84.5	37.54	0	0	122.04	3.04	127.8	0	0	130.84	316.92	0.5%		
Sweden	2.16	0.92	18.72	0	21.8	3.92	13.6	120.64	0	138.16	0.44	17.32	239.58	2.3	259.64	419.60	0.7%		
Taiwan	0	0	0	**44.74**	44.74	0	0	0.1	**68.96**	69.06	0	0.18	39.4	**498.9**	538.48	652.28	1.1%	613	2.1%
Tanzania	0.62	2.74	0	0	3.36	0.56	1	0	0	1.56	40.06	5.74	0	0	45.8	50.72	0.1%		
Trinidad and Tobago	2.3	2.7	2.82	0	7.82	0	2.24	33.6	0	35.84	0.04	12.08	80.96	0	93.08	136.74	0.2%		
Tunisia	1.62	0.96	0	0	2.58	18.12	8.54	0.56	0	27.22	58.86	174.72	2.86	0	236.44	266.24	0.4%		
Turkey	0	0	0	0.02	0.02	0	0	0	0.14	0.14	0	0.48	0.94	2.9	4.32	4.48	0.0%		
Ukraine	51.72	94.56	0	0	146.28	19.56	64.82	0	0	84.38	17.22	62.58	0	0	79.8	310.46	0.5%		
United Kingdom	0	0	53.88	**113.96**	167.84	0	0	46.28	**417.48**	463.76	0	0	0.54	**1,840.90**	1,841.40	2,473.00	4.1%	2,372	8.0%
United States (48)	33.16	128.34	56.88	**15.68**	234.06	7.8	285.56	52	**49.22**	394.58	107.86	700.18	404.82	248.2	1,461.10	2,089.70	3.4%	313	1.1%
Uruguay	0	121.32	26.1	0	147.42	0	86.1	7.64	0	93.74	0	59.48	51	5.4	115.88	357.04	0.6%		
Vanuatu	0	0	0.06	0	0.06	0	0	0.1	0	0.1	0	21.58	83.24	11.68	116.5	116.66	0.2%		
Venezuela	10.58	23.4	1.1	**55.24**	90.32	10.14	62.76	20.08	14.78	107.76	29.98	159.2	108.98	73.22	371.38	569.46	0.9%	143	0.5%
Viet Nam	47.12	54.64	69.1	**25.58**	196.44	75.58	70.78	74.46	**59.2**	280.02	81.02	122.06	101.3	161.36	465.74	942.20	1.5%	246	0.8%
Western Sahara	10.02	17.26	2.8	0	30.08	27	70.36	17.52	0	114.88	9.7	158.44	96.52	0	264.66	409.62	0.7%		
Yemen	1.02	2.96	3.06	0	7.04	1.8	7.46	15.16	0	24.42	12.04	13.34	74.86	0	100.24	131.70	0.2%		
Unassigned*	72.38	120.34	195.32	**479.1**	867.14	80.36	86.42	123.64	**1,122.90**	1,413.40	248	723.28	1,044.60	**8,900.40**	10,916	13,197.00	21.6%	**10,502**	
Global Total	973.4	1,881.90	2,332.80	1,740.50	6,928.70	952.08	2,689.00	2,395.30	4,419.30	10,455	2,935.40	7,595.10	11,743	34,511	56,785	**74,169.00**		**40,269**	
Without Unassigned	901.02	1761.56	2137.48	**1261.4**	6061.56	871.72	2602.58	2271.66	3296.4	9041.6	2687.4	6871.82	10698.4	25610.6	45869	**60,972.00**	100.0%	**29,766**	100.0%